AN EXPERIMENTAL STUDY TO DETECT CAVITATION EROSION FOR DIFFERENT COATED SURFACES

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This paper presents an experimental study to investigate the cavitation damage caused by bubble collapses in different surfaces coated by different methods. A cavitation air jet rig was constructed adapting similar specifications given in ASTM G134 Standard Test Method for cavitating liquid jet and the cavitation erosion tests were performed using this air jet rig. The tests were carried out under specified conditions in bubbly flow for the sample surfaces of CU1 (nickel-aluminium-bronze) alloy and CU3 (manganese-bronze) alloy in the cavitation test rig, which was set-up for this study at ITU. The samples were coated by acrylic paint using different techniques such as dipping, spraying, brushing and acrylic paint by pen. One set of samples was left uncoated as the reference. Flow rate of the air and water, and stand-off distance of the samples were investigated and optimized. The tests were performed by intervals of 4 hours. Cavitation erosion on the surface of the samples was examined using a Reflective Light Microscope (RLM). Complementary experimental investigations, considering different test durations and coating techniques were conducted in the cavitation test rig. Results indicated a strong influence of the exposure time on the damage rate of the samples. On the other hand, it has been observed that the effect of stand-off distance is crucial on the development of cavitation erosion. The ultimate goal of the experimental study performed is try to explore similarity of the cavitation erosion formation to the erosion tests at cavitation tunnels for propellers. This will enable the replication of the propeller material and paint combination as an erosive indicator in a simpler setup.

1. Introduction

Cavitation damage is caused by bubble collapses in the vicinity of a solid surface. Weak cavitation impacts have small impact energy, which cannot produce elastic or plastic deformation on materials. Cavitation erosion does not take place in this situation. On the other hand, strong cavitation impacts have large impact energy, which generates plastic deformation and causes damage with mass loss. It is proposed that only cavitation impacts that are larger than a certain threshold level affect the cavitation erosion of materials [16].

Cavitation erosion test techniques include the utilization of ultrasonic vibration devices to generate the cavitation [2, 9, 13], cavitation flow loops with strong flow separation, vortex or venturi effects [5, 6, 7, 8] rotating discs and submerged cavitating liquid jets [3, 14, 15] and other methods. Some of these techniques are standardized and follow the American Society for Testing and Materials (ASTM) Standards [1]. The ultrasonic technique and the liquid jet technique are the two most popular laboratory techniques for testing cavitation erosion characteristics of materials [10]. It should be particularly specified that the method used for this paper is cavitating air jet and it is different from the above methods. It is very similar to liquid jet technique, however it uses air instead of water to blow from nozzle.

Cavitation erosion involves both liquid flow and material properties. On the liquid side, cavitation erosion depends upon the ''aggressiveness'' of the cavitating flow, defined in terms of the frequency and intensity of the collapses. On the material side, it depends upon the material properties which govern the response of the boundary to the cavitating flow. The actual damage will be the result of the competition between the cavitation intensity and the material strength. Material strength may be characterized by conventional properties such as hardness, strain energy, or ultimate resilience. Correlations between cavitation erosion (typically mass loss) and material properties are unfortunately far from being universal and are generally valid only within a given class of materials and cavitation intensities. This is the reason why researchers have recently attempted to develop analytical techniques as opposed to correlative techniques [10].

Cavitation test on a model-scale are normally carried out in traditional cavitation tunnels or less frequently using depressurised towing tanks according to guidelines and procedures set forth by the ITTC. On the other hand cavitation erosion testing of smaller samples or materials is performed on a smaller and less complicated scale, and according to ASTM standards. The stipulated tests are ASTM G62-98 which is the "Standard test method for cavitation erosion using vibratory apparatus" and ASTM G134-95 "Standard test method for erosion of solid materials by cavitating liquid jet" [1]. The secondary one is the subject of this study.

The principal aim of this study is to determine the resistance of the sample surfaces of nickel-aluminium-bronze alloys and manganese-bronze alloys to cavitation erosion. This aim is achieved through a series of objectives.

1- Constructing a cavitation air jet rig and performing experiments to investigate cavitation erosion of solid materials by this cavitating air jet adapting the specifications given in ASTM G134 Standard Test Method for cavitation erosion.

2- Analyzing the surfaces of manganese-bronze (CU1) and nickel-aluminium-bronze (CU3) alloys samples using microscopic (RLM) techniques.

3- To explore similarity of the cavitation erosion formation with the erosion tests at cavitation tunnels for propellers.

Within the above context this paper presents an experimental study to investigate the cavitation damage of different coated surfaces that is caused by bubble collapses. A cavitation air jet rig is constructed adapting similar specifications given in ASTM G134 Standard Test Method for cavitating liquid jet and cavitation erosion tests were performed using that air jet rig. Section 2 gives some information about cavitation cell tests used to generate cavitation and Section 3 presents the description of experimental set-up and test conditions. Section 4 presents the results and discussions and finally Section 5 draws conclusions from the study.

2. Cavitation Cell Tests

Several laboratory techniques to generate cavitation have been used conventionally to study cavitation erosion in a controlled environment and in an accelerated manner. Accelerated erosion laboratory techniques include ultrasonic flows, cavitation flow loops with strong flow separation, rotating disks, cavitating venturi flows, vortex generators, and submerged cavitating jets [2, 4, 8, 15] as mentioned in the introduction part.

2.1. Ultrasonic cavitation erosion testing – ASTM G32

In ultrasonic cavitation tests, the cavitation is generated by a vibratory device employing a magnetostrictive ultrasonic horn. A sample "button" of the material being tested is affixed to the end of the horn and is subjected to cavitation resulting from the vibrations of the horn. A cavitation hemispherical cloud forms at the tip of the horn and executes severe dynamics resulting in bubble cloud growth and collapse. In an "alternative" G-32 test configuration (also known as a stationary specimen method), the horn tip is placed at a small distance from the stationary material sample and a rather cylindrical cavitation cloud is generated in between the sample and the face of tip of the horn equipped with a strongly cavitation resistant "button" (e.g. Titanium) [4]. In the standard G-32 test the temperature, liquid beaker volume, horn tip submergence beneath the free surface, frequency, and amplitude of the oscillations are all prescribed by the ASTM method [1].

2.2. Cavitating jets – ASTM G134 and others

Cavitating jets can be used to test different surfaces and compare the cavitation erosion resistance of solid materials. The test is carried out under specified conditions in a specified liquid, usually water [17].

Cavitation intensity produced by cavitating jets can be varied in a very wide range through adjustment of the type of jet, the jet velocity, the jet diameter, the jet angle, the stand-off distance, the ambient pressure in which they are discharged [4]. This flexibility makes a cavitating jet a great research and test tool to study parametrically the effect of cavitation intensity on materials behavior. The cavitation generated by a cavitating jet provides realistic cavitation bubble clouds with distribution of various size micro bubbles, shear flows with vortices, and dense bubble clouds, which collapse on the sample. With the control of the operating pressure, the jet angle, and the stand-off, the testing time can be adjusted to provide either quick erosion for initial screening or time-accelerated erosion more relevant to the real flows [4].

Standard test method for erosion of solid materials by cavitating liquid jet which serves the basis of the cavitation testing is planned to carry out in this study. Even though the testing fluid is water, the fluid that spring from the nozzle is air. So the method used in this study is a simplified cavitating air jet.

This method is planned to be used in this study in order to reproduce and study the effects of cavitation on a composite material in the laboratory by inducing cavitating jets. It is basically achieved by the maintenance of a high pressure difference in a test chamber which would house a nozzle with a specific diameter and also a sample which would normally be cylindrical and facing the nozzle so as to have the bubbles issuing from the nozzle collapse on it. A liquid must also be present inside the test chamber and could either be allowed to run to waste or by having the liquid recirculated by adding a reservoir and a pump to the set-up.

The use of a cavitating jet and a nozzle to assess the extent of resistance a material has to cavitation or the effects of cavitation erosion was first proposed by A. Lichtarowicz. This was done in 1972 through an article titled 'Use of a simple cavitating nozzle for cavitation erosion testing and cutting' [11]. In this study, it was assumed that flow splits up at the sharp inlet edge of a long orifice nozzle. Assuming that the pressure difference within the nozzle increases, the pressure levels at the separated area would eventually get to the vapour pressure of the liquid and cavitation surfaces. The cavitated bubbles at this area of the nozzle would continue to increase in length with increased pressure difference by the time they eventually outgrow the bore length and appear as a cavitation trail outside the orifice. The downstream pressure, which is higher than the vapour pressure, causes the bubbles to collapse. Materials present in these areas are subjected to cavity collapse and therefore cavitation erosion.

In 1979, Lichtarowicz put this theory into practice by carrying out an experiment involving a submerged cavitating jet which was used to actualise erosion on a test sample. From the experiment it was concluded that the erosion inception would be contingent on the velocity of the cavitating jet, the downstream pressure (pressure present in the test chamber) and the stand-off distance. The conclusions drawn show the method is appropriate for testing of cavitation erosion on materials [12]. To also lend credence to this theory put forward by Lichtarowicz, some other experiments have been carried out according to the specifications and stipulations in [12]. Details of the set-up and results of some other experiments can be found in [18].

3. Experimental Study to Detect Cavitation Erosion for Different Coated Surfaces

The cavitation test rig built in the Istanbul Technical University Faculty of Naval Architecture and Ocean Engineering, Ilham Artuz Marine Technology and Oceanography Laboratory in consideration of the standards of ASTM [1]. All the tests in this study were performed in this laboratory.

3.1. The cavitation test rig and components

The cavitating test rig set-up used in this study consists of 6 different main components; cavitation chamber, peristaltic pump, water tank, air compressor, air regulator (pressurere gulator) and flow meter. The cavitation test rig is shown in Fig. 1.

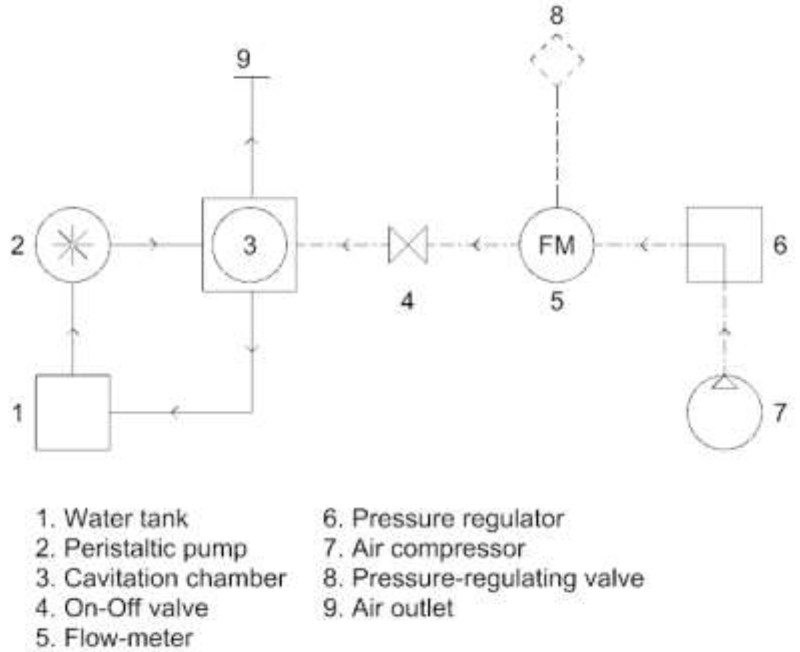

Fig. 1 – *The cavitation test rig*

A cavitating jet supplied from a constant pressure source (Pu), discharges, through a long-orifice nozzle, into a chamber held at specified constant pressure (Pd). A cylindrical sample (Fig. 13) is mounted coaxially with the nozzle so that the stand-off distance between the nozzle inlet edge and the sample face can be set at any required value. Cavitation chamber assembly is shown in Fig. 2.

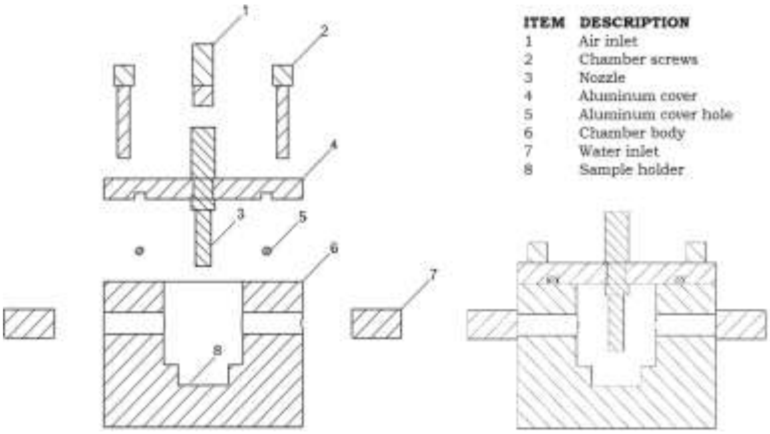

Fig. 2 – Cavitation chamber assembly, left: exploded, right: joined

3.2. Cavitation test chamber components

The cavitation test chamber is made of plexiglass material which is a transparent thermoplastic material and would make possible the visualisation of the cavitation tests. It consists of pressure vessel, cover (nozzle holder), air nozzle, joints and seals, o-ring, water inlet and drainage elements. There is an aluminium cover on the top of the chamber. There are two pneumatic nipples on the center of the cover which are used for inlet and outlet of the air. There are six screws to immobilise the aluminium cover to the chamber. The cavitation test chamber used in this study is shown in *Fig. 6*.

Fig. 3 shows the CAD model of the cavitation chamber aluminium cover of the chamber, pneumatic nipples, screws and base part of the chamber, the sample cover, water inlet and outlet hoses.

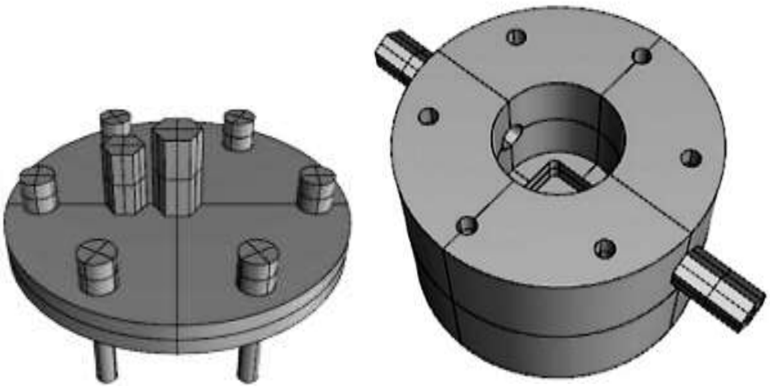

Fig. 3 – Aluminium cover of the chamber, pneumatic nipples, screws (on the left side), Base part of the chamber, the sample cover, water inlet and outlet hoses (on the left side)

Both sides of the cavitation test chamber are openings that enable the test water to be recirculated via the aid of a peristaltic pump and two pipes. Components of the cavitation test chamber is shown in *Fig. 4*.

Fig. 4 – Cavitation test chamber components

At the base of the chamber a sample holder is fixed in place, the function of this is to make sure the sample is always in the same angular position while facing the jets emanating from the inlet edge of the nozzle and for the sample to be placed back exactly at the same spot when returned after an analysis. At the bottom of the nozzle is the upstream pressure inlet pipe which supplies the pressurized air to the chamber through the nozzle.

The dimensions of the test chamber are thus, the diameter of the aluminium cover and also the chamber is 100 mm, the length of the entire chamber is 80 mm while the top of the chamber that acts as a nozzle holder of sorts is 10 mm (thickness of the aluminium cover). Length of the nozzle is 32 mm and diameter of the nozzle is 7.50 mm. These dimensions are on a scale just enough to achieve the target of this cavitation jet experiment and were adopted from ASTM [1]. The aluminium cover and nozzle are shown in Fig. 5.

Fig. 5 – Aluminium cover and nozzle

The shape and dimensions of the nozzle is as specified by ASTM [1]. The diameter of the nozzle is 3mm, the length of the nozzle present inside the chamber is determined by the stand-off distance of the test. It is made of steel which is can considerable resistance to both erosion and corrosion.

The cavitation chamber used in the experiments of this study is shown in *Fig. 6*.

Fig. 6 – Cavitation test chamber

3.3. Test samples

The test samples used in cavitation erosion tests are made of CU1 (manganese bronze) alloy and CU3 (nickel-aluminium-bronze) alloy. They are 20 mm diameter and 10 mm height cylinder. They are coated with acrylic coatings by different techniques such as brushing, dipping, spraying and acrylic pen. Samples coated with different coating techniques used in the cavitation tests are shown in *Fig. 7a* and *Fig. 7b*.

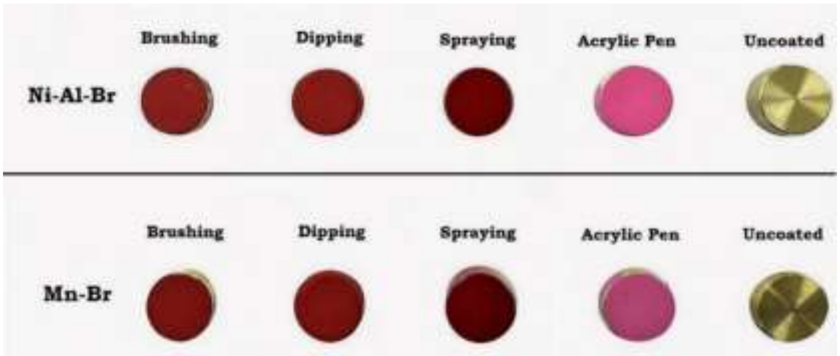

Fig. 7a – Samples coated with different coating techniques for the first test case

Fig.7b – Samples coated with different coating techniques for the second test case

3.4 Test conditions and test procedure

ASTM [1], states that if different environmental conditions result in deviation from the specified test conditions, these different standard conditions should be noted. The different conditions of this cavitation test are due to the limitations in the pressure levels available. The test conditions are;

- Test Liquid : Fresh water
- Temperature : 15 (±3) °C (water temperature at nozzle inlet is assumed to be the same as the temperature at which the experiment is being carried out).
- Flow rate of peristaltic pump: 300 ml/min
- Compressor outlet pressure: 2 bar
- Pressure at pressure regulator: 2-4 bar
- Flow rate of flow meter: 300 ln/h (5 l/min) and 450 ln/h (7.5 l/min)
- Stand-off distances : 5 mm, 2.5 mm, 1mm.

The test procedure explained hereinafter is adopted from the G134-95 method [1]. Before the main cavitation erosion tests on the composite materials are commenced all necessary parameters have to be determined. Fresh water is determined as the test liquid for the experiments because cavitation tunnel experiments are carried out in fresh water, therefore the density and other necessary parameters of the test fluid match the operational conditions of cavitation tunnel experiments for propellers. Temperature of the tests was around 15°C temperature (±3) °C. The corresponding vapour pressure of this temperature is given as 1599 Pa. This temperature therefore is the same as the temperature at the nozzle inlet.

Peristaltic pump which has a maximum flow rate of 400 ml/min is used to keep the fluid in the chamber at the required level, and to recirculate the test fluid which is fresh water. Different flow rates are tried and flow rate of the pump is kept flow rate of 300 ml/min during all of the tests.

The stand-off distance *(Fig. 8)* which is defined as 'the distance between the inlet edge of the nozzle and the target face of the sample' ASTM [1] is a major parameter in the cavitation erosion tests. Because it determines the extent of cavitation damage on the test material depending on the given parameters. Stand-off distance from the nozzle to the sample are measured and changed to optimum conditions.

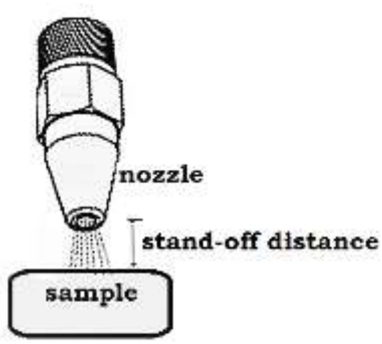

Fig. 8 – Stand-off distance

Series of short tests were performed on to determine the stand-off distance. This was done at different randomly chose stand-off distances, but the pressure parameters remain the same. The stand-off distances of the cavitation erosion tests were decided as 5 mm, 2.5 mm and 1 mm. The samples were stored in a store which made of polystyrene to adjust the stand-off distance.

Different flow rates are tried and flow rate of the air is 300 ln/h (5 l/min) for the first test case and 450 ln/h (7.5 l/min) for the second test case.

Procedure of the cavitation erosion experiments

- Weight the sample with the precision scales
- Record the mass of the sample
- Place the sample into the polystyrene store
- Adjust the stand-off distance
- Peristaltic pump is turned on to fill the cavitation chamber with the water
- Air compressor is turned on
- The flow rate is set with the flowmeter
- The pressure levels are set and water level of the chambe is controlled for 15 minutes
- After 4 hours period is reached experiment is stopped
- Water is drained from test chamber
- Sample is put into the desiccator (for drying)
- Weight the sample with the precision scales again
- Surface of sample is analysed and photographed using a Reflective light Microscope (RLM).

❖ After each test, samples are put into the desiccator and waited until the next test.

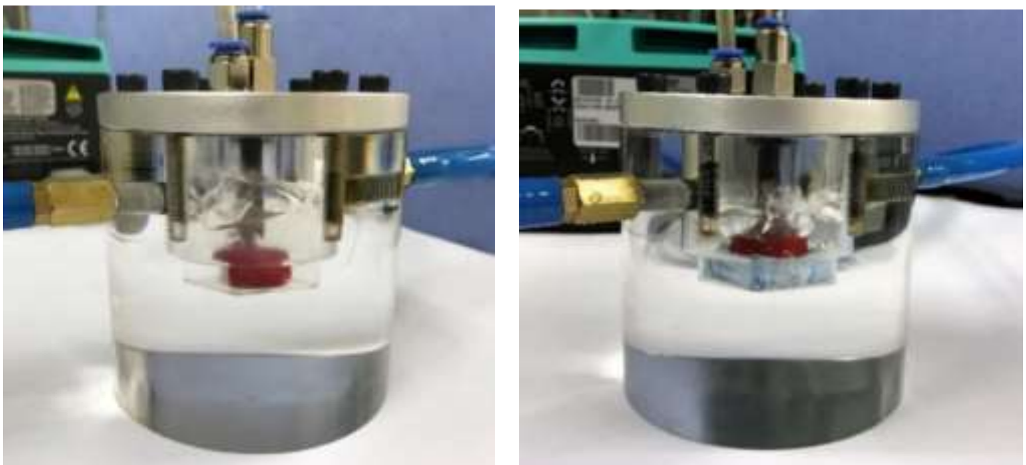

Fig. 9a – A figure of cavitation erosion test in 300 ln/h airflow at 5 mm stand-off distance (on the left side) and 1 mm stand-off distance (on the right side)

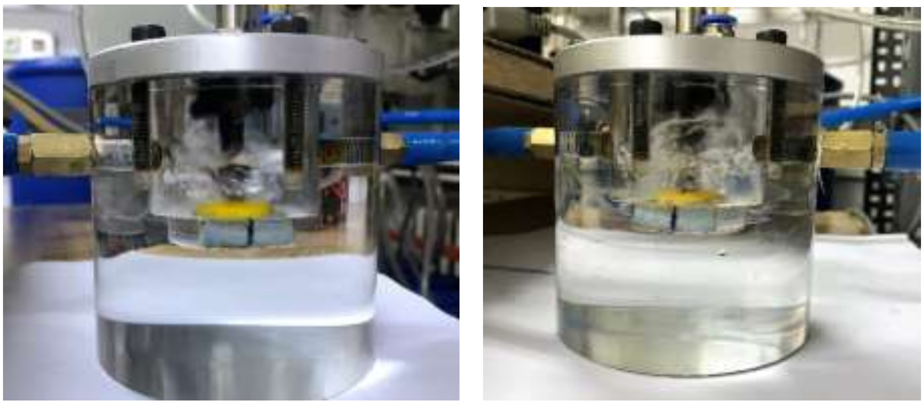

Fig. 9b – A figure of cavitation erosion test in 450 ln/h airflow at 5 mm stand-off distance (on the left side) and 1 mm stand-off distance (on the right side)

3.5. Microscope measurements

Surfaces of the samples analysed using a Reflective Light Microscope (RLM). A diameter of 10 mm on the samples surface is analysed. Some visuals from the first cavitation tests are seen in the following section. Analysis of the surface of the sample of CU3 alloy coated with dipping technique, RLM microscope is shown in *Fig. 10*.

Fig. 10 – Analysis of the surface of the sample using RLM microscope

4. Results of the Cavitation Erosion Tests

Samples are located at the stand-off distances of 5 mm, 2,5 mm and 1 mm respectively. The only difference between the first and second cases is airflow rate. The first tests cases are conducted in 300 ln/h (5 l/min) flow rate while the second test cases were conducted in 450 ln/h flow (7.5 l/min).

During all the test cases, water quality and temperature, water pressure, airflow rate, stand-off distance and all other variables were kept constant. Surfaces of the samples were analysed after each four hours tests. These erosion tests were conducted in 1 mm stand-off distance.

Initial, 4 hours, 8 hours and 12 hours cavitation test conducted surfaces of the CU1 and CU3 alloys samples are compared visually using RLM. According to the test results, it can be said that, cavitation erosion on the sample surfaces are increasing after each of the tests.

4.1. Results of the cavitation erosion tests of Manganese-Bronze samples (First case, airflow rate=5 l/min)

Cavitation erosion tests results of the surfaces of the Nickel-Aluminium-Bronze samples that were coated by techniques of brushing, dipping, spraying, pen and uncoated are shown in Figures 11-15, respectively. The figures on the left side show initial conditions and the figures on the right side show 4 hours tested surface. The figures on the left-bottom side show 8 hours tested surfaces and the figures on the right-bottom side show 12 hours tested surfaces.

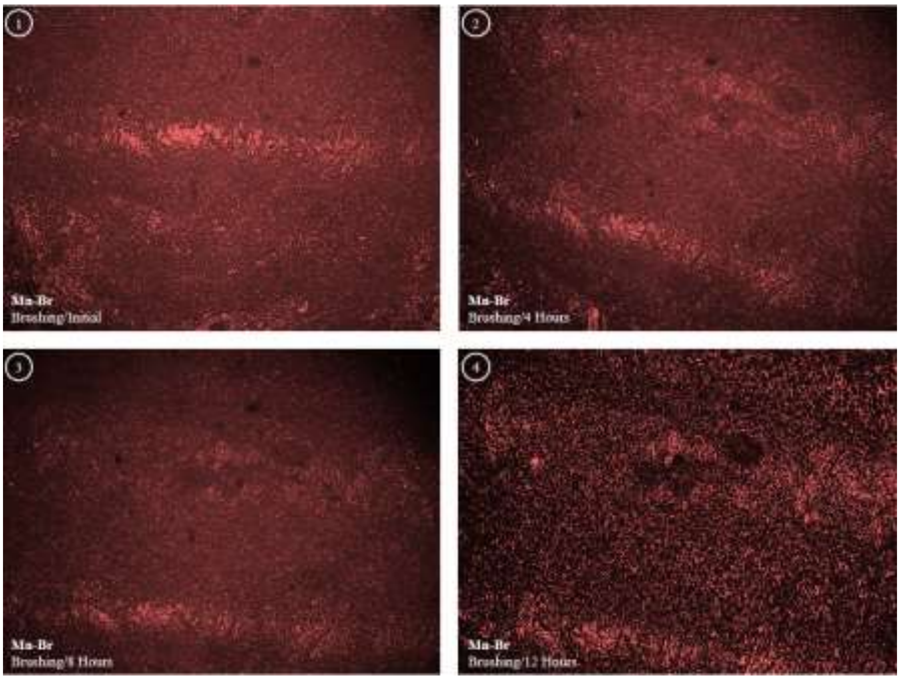

Fig. 11 – Brushing technique results of Manganese-Bronze alloy sample

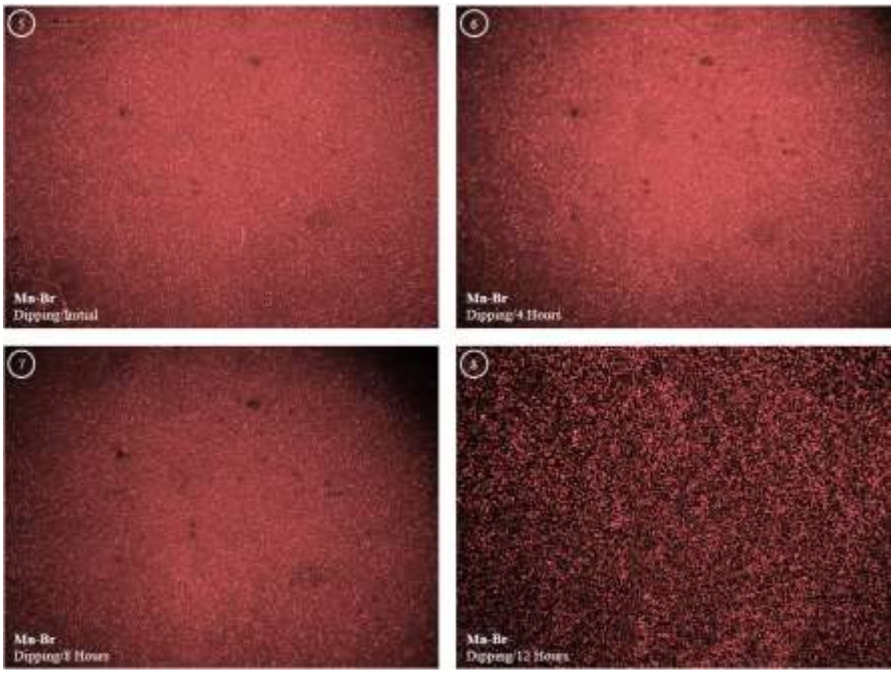

Fig. 12 – Dipping technique results of Manganese-Bronze alloy sample

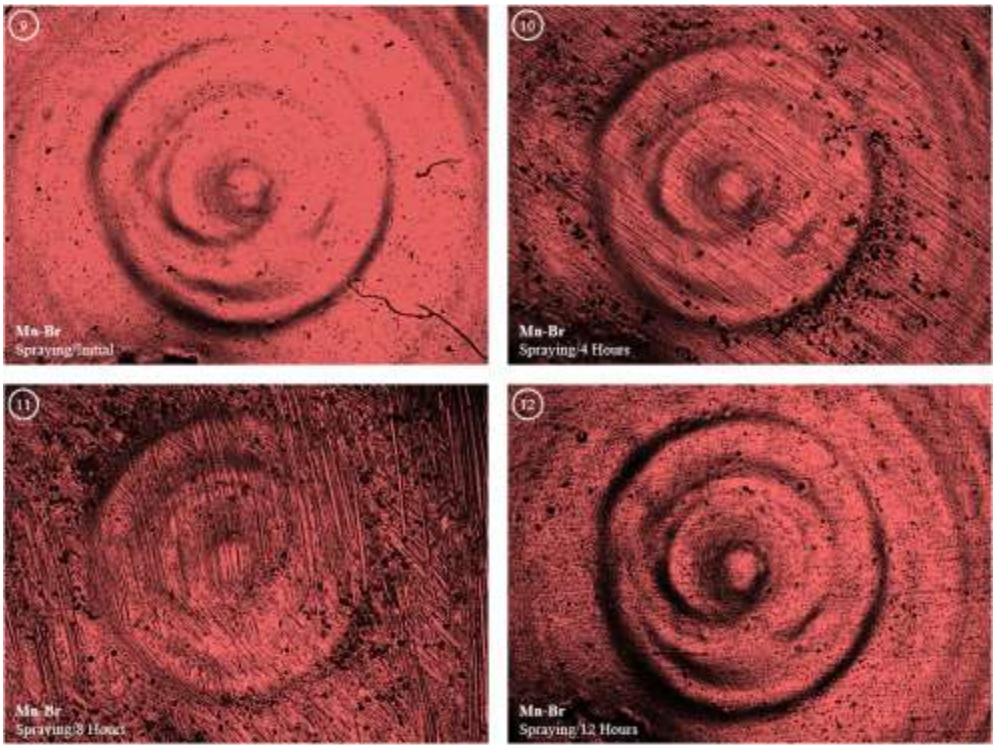

Fig. 13 – Spraying technique results of Manganese-Bronze alloy sample

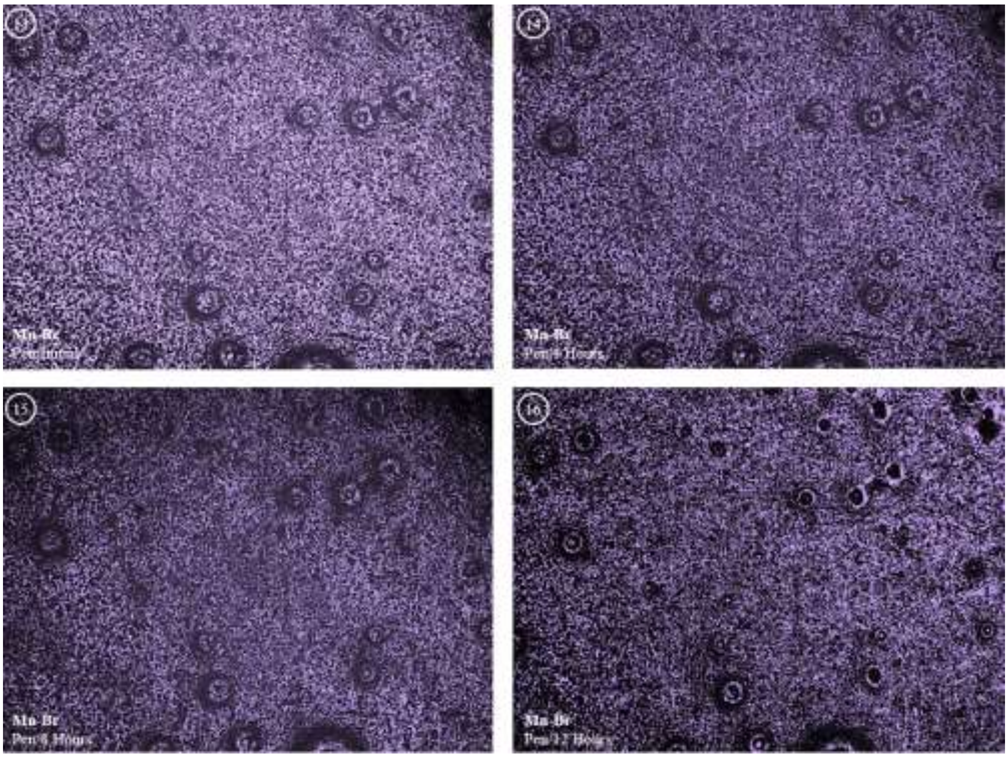

Fig. 14 – Pen technique results of Manganese-Bronze alloy sample

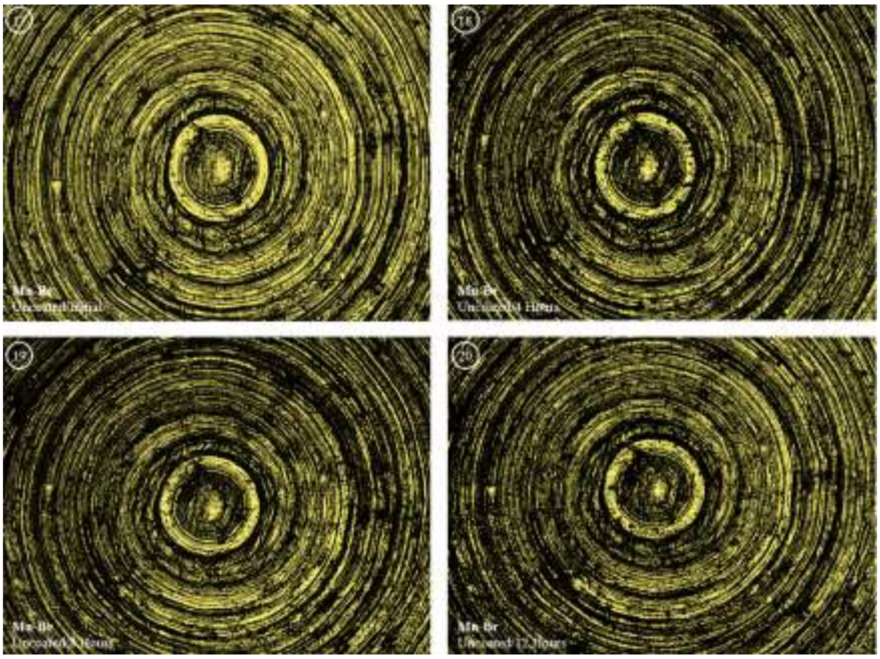

Fig. 15 – Uncoated results of Manganese-Bronze alloy sample

4.2. Results of the cavitation erosion tests of Nickel-Aluminium-Bronze samples (First case, airflow rate=5 l/min)

Cavitation erosion tests results of the surfaces of the Nickel-Aluminium-Bronze samples that were coated by techniques of brushing, dipping, spraying, pen and uncoated are shown in Figures 16-20, respectively. The figures on the left side show initial conditions and the figures on the right side show 4 hours tested surface. The figures on the left-bottom side show 8 hours tested surfaces and the figures on the right-bottom side show 12 hours tested surfaces.

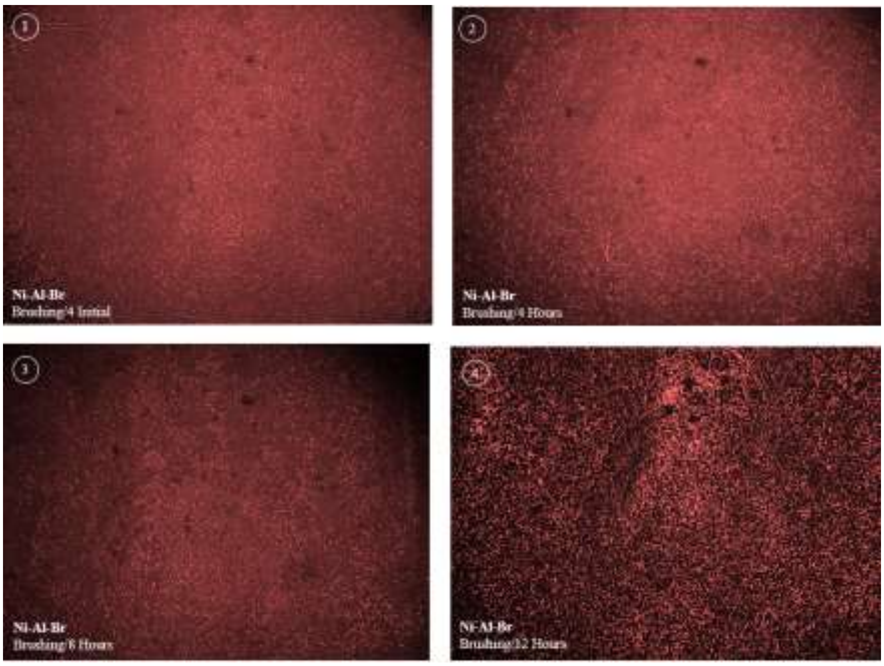

Fig. 16 – Brushing technique results of Nickel-Aluminium-Bronze alloy sample

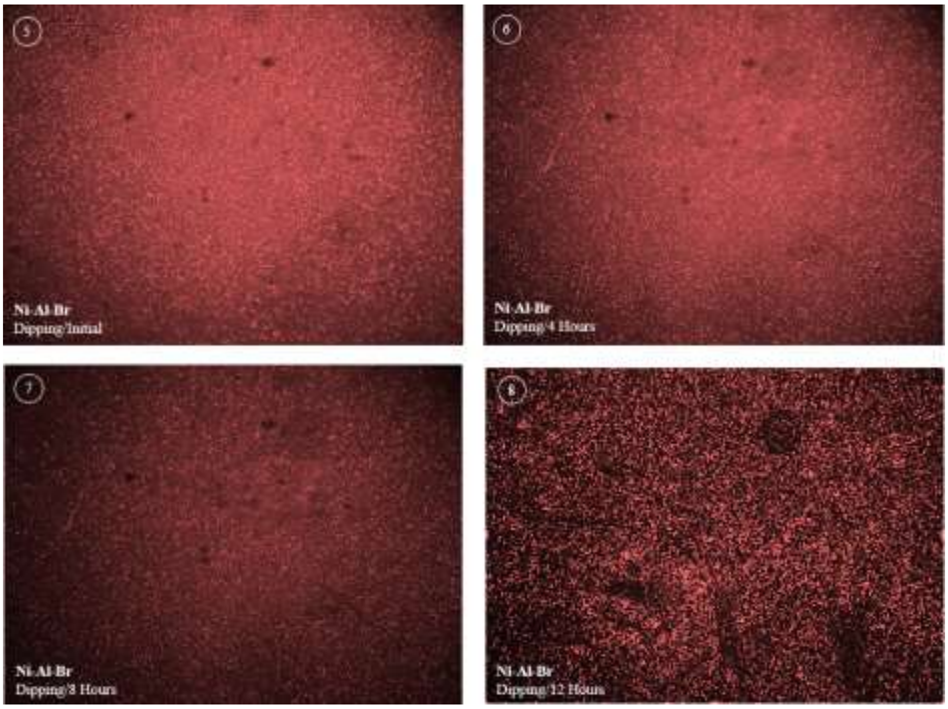

Fig. 17 – Dipping technique results of Nickel-Aluminium-Bronze alloy sample

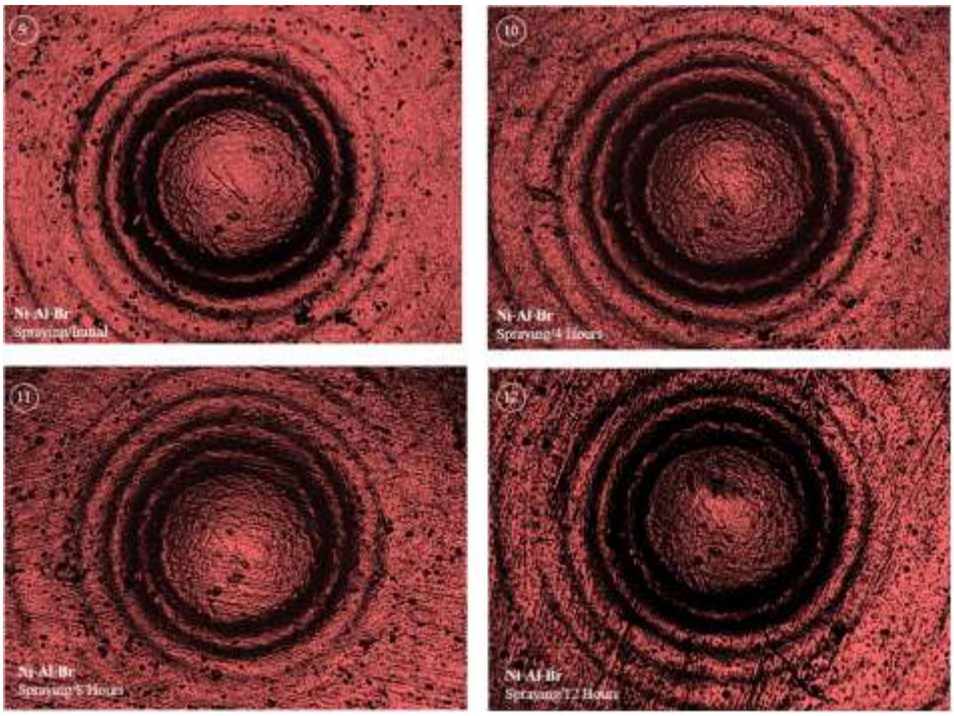

Fig. 18 – Spraying technique results of Nickel-Aluminium-Bronze alloy sample

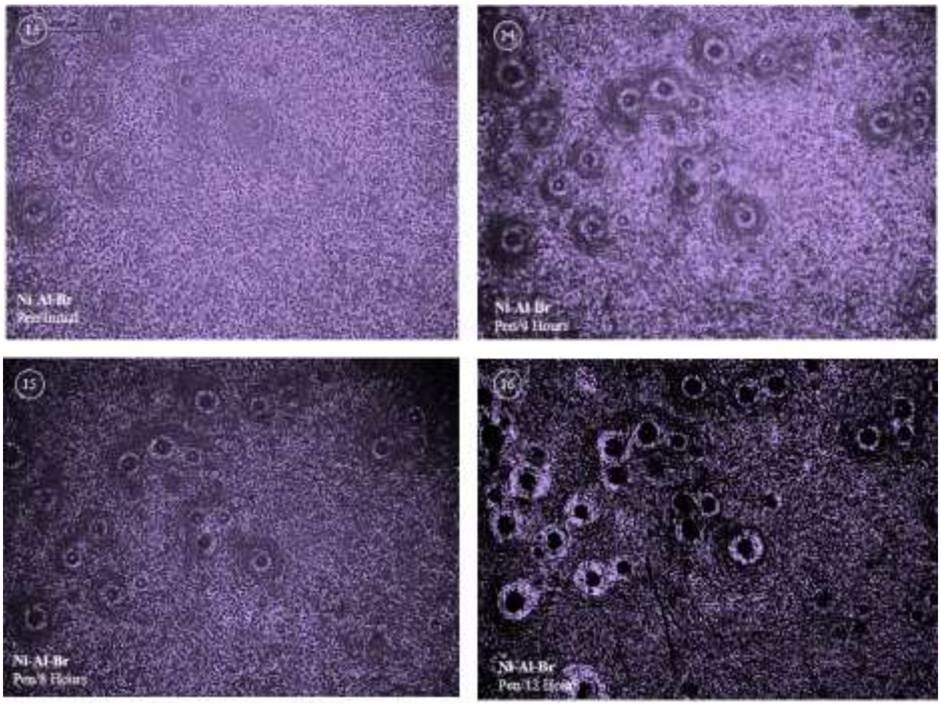

Fig. 19 – Pen technique results of Nickel-Aluminium-Bronze alloy sample

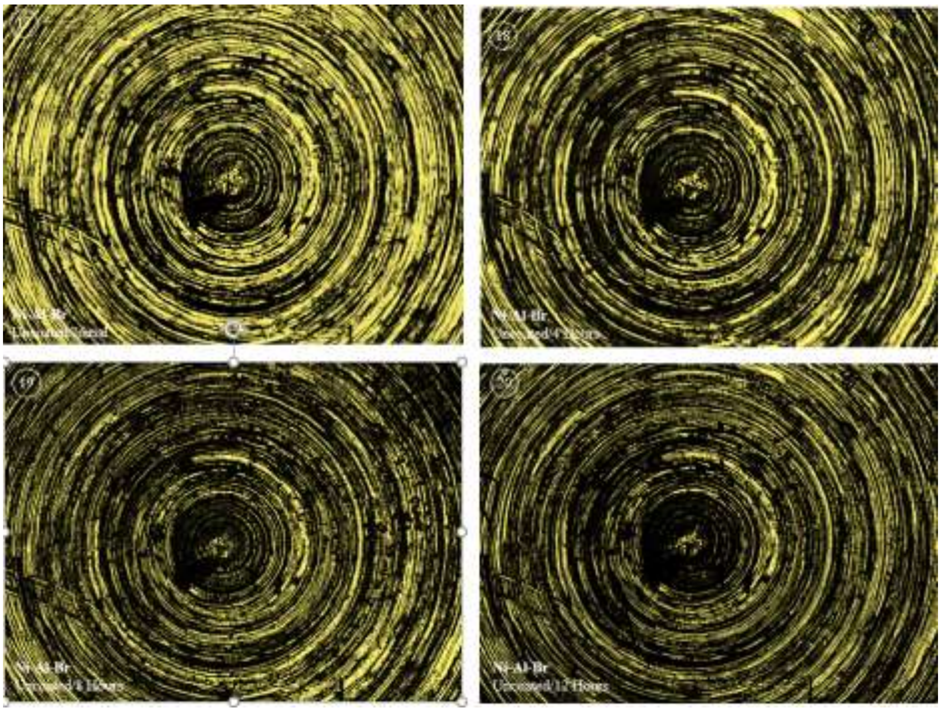

Fig. 20 – Uncoated results of Nickel-Aluminium-Bronze alloy sample

Almost all figures for results of Manganese-Bronze and Nickel-Aluminium-Bronze alloy samples show that, after each 4 hours test conducted, surface of the alloy seems darker than the initial conditions. This means that cavitation tests made the surface more damaged and created some irregularities on the surfaces.

Figures 11-20 show that, after 12 hours test conducted, surface of the both CU1 and CU3 are seems darker and rougher than the initial conditions. This means that cavitation tests made the surface more damaged and created some irregularities on the surfaces.

4.3. Results of the cavitation erosion tests of Manganese-Bronze samples (Second case, airflow rate=7.5 l/min)

Surfaces of the Manganese-Bronze samples that were coated by techniques of brushing, dipping, spraying, pen and left uncoated. Figures generated by RLM are shown in Figures 21-25, respectively. The figures on the left side show initial conditions and on the right side show 4 hours tested surface. It is seen that the samples on the right side are darker and they have damaged parts on their surface.

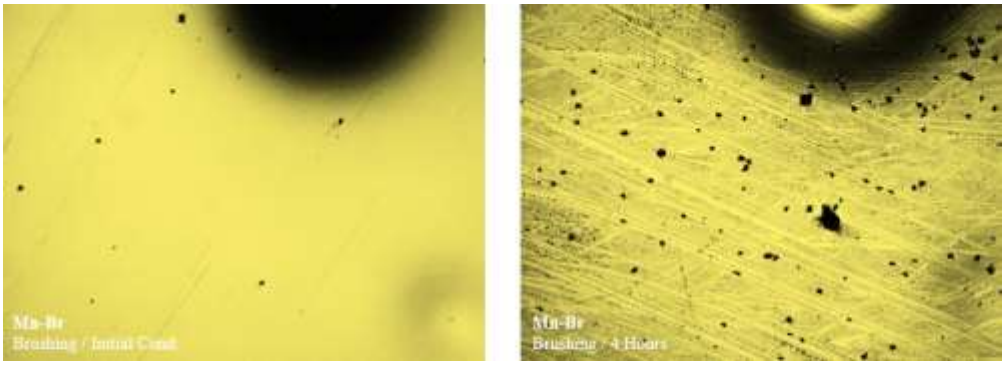

Fig. 21 – Brushing technique results of Manganese-Bronze alloy sample

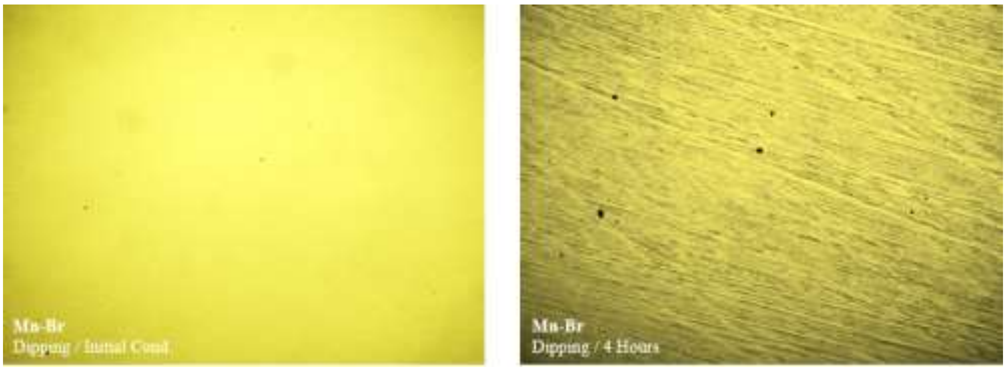

Fig. 22 – Dipping technique results of Manganese-Bronze alloy sample

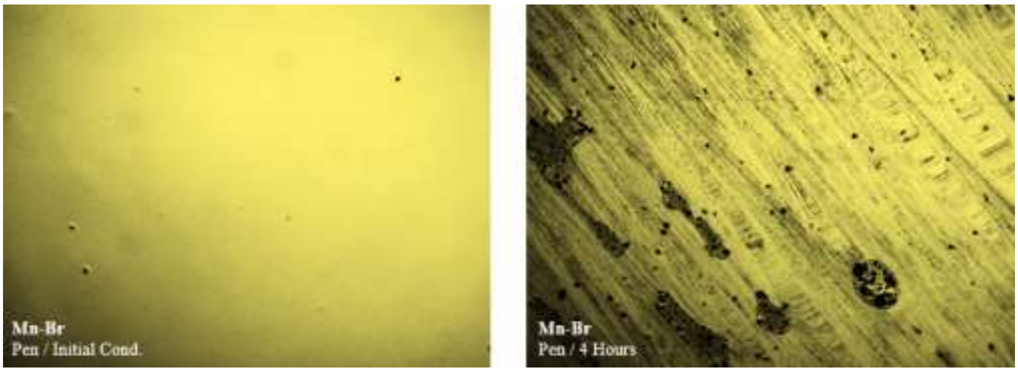

Fig. 23 – Pen technique results of Manganese-Bronze alloy sample

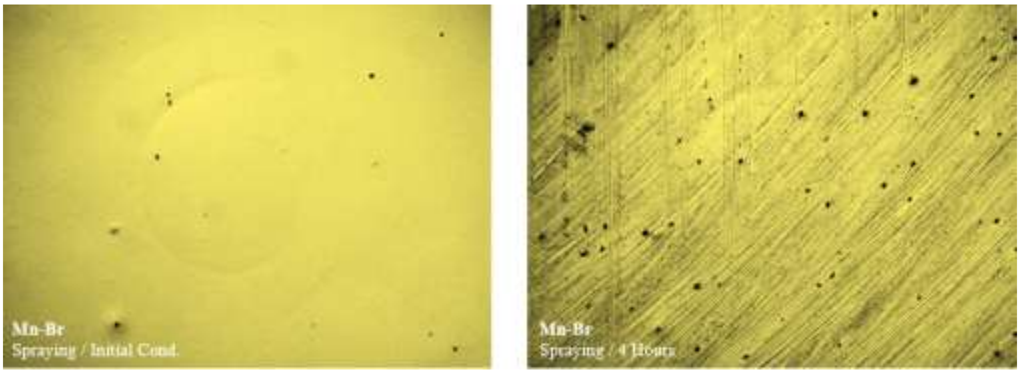

Fig. 24 – Spraying technique results of Manganese-Bronze alloy sample

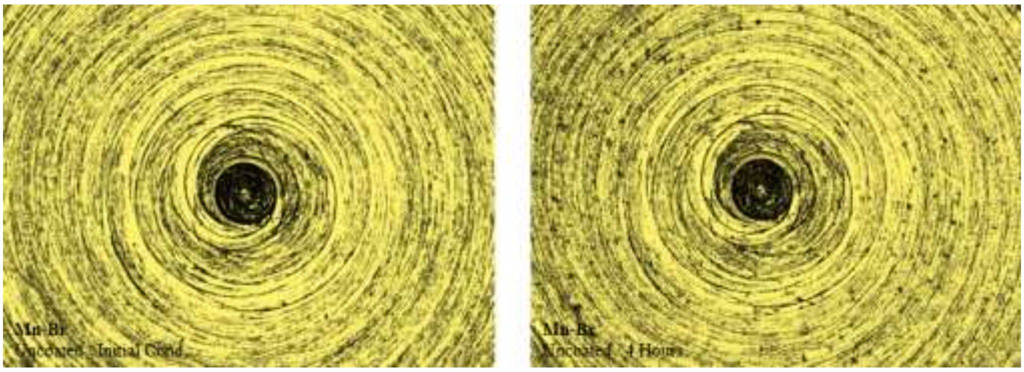

Fig. 25 – Uncoated results of Manganese-Bronze alloy sample

4.4. Results of the cavitation erosion tests of Nickel-Aluminium-Bronze samples (Second case, airflow rate=7.5 l/min)

Cavitation erosion tests results of the surfaces of the Nickel-Aluminium-Bronze samples that were coated by techniques of brushing, dipping, spraying, pen and left uncoated are shown in Figures 26-30, respectively. The figures on the left side show initial conditions and the figures on the right side show 4 hours tested surface. The samples on the right side have damages on their surface. This means cavitation erosion on the surface increases by the test time.

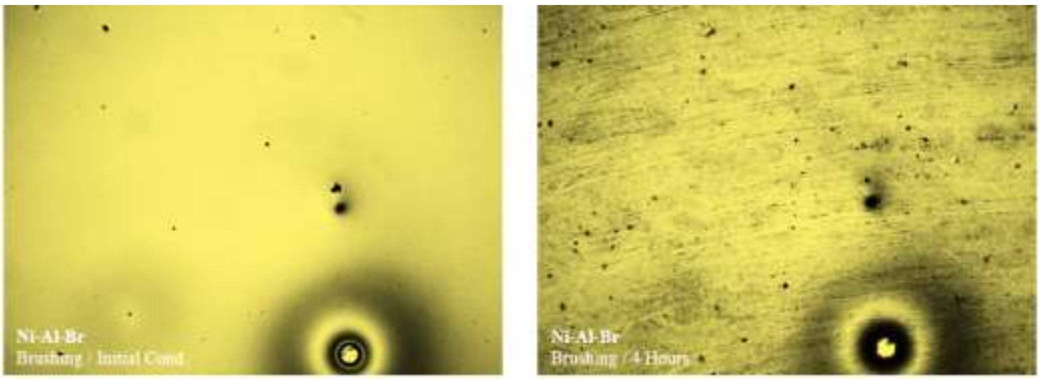

Fig. 26 – Brushing technique results of Nickel-Aluminium-Bronze alloy sample

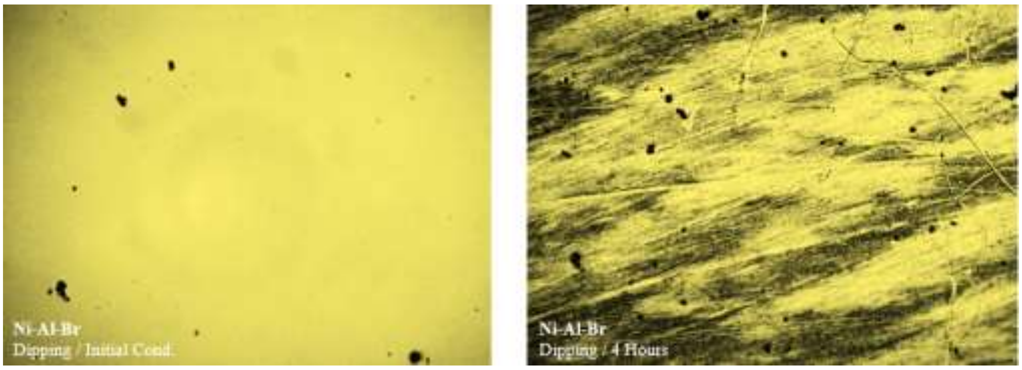

Fig. 27 – Dipping results of Nickel-Aluminium-Bronze alloy sample

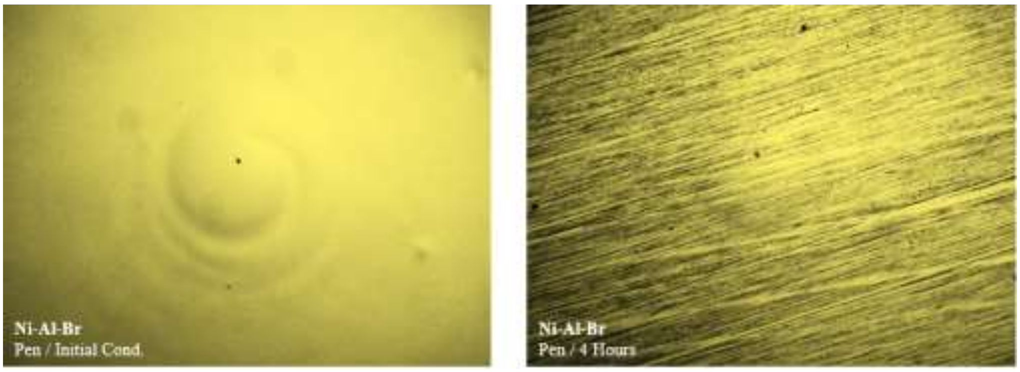

Fig. 28 – Pen technique results of Nickel-Aluminium-Bronze alloy sample

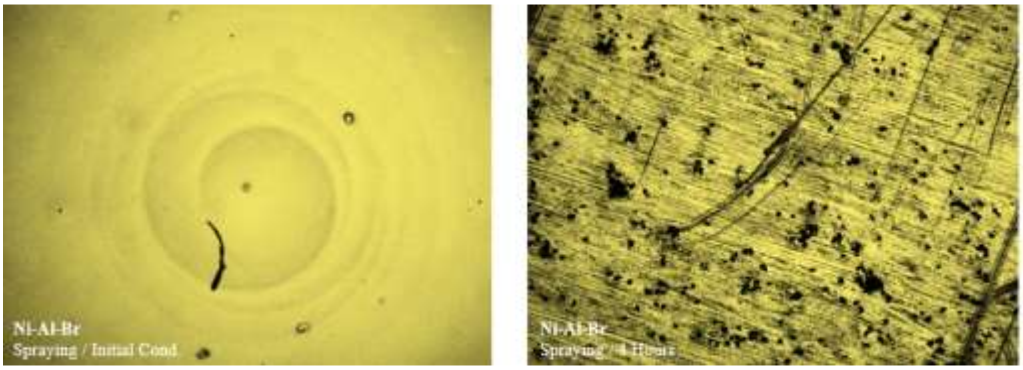

Fig. 29 – Spraying technique results of Nickel-Aluminium-Bronze alloy sample

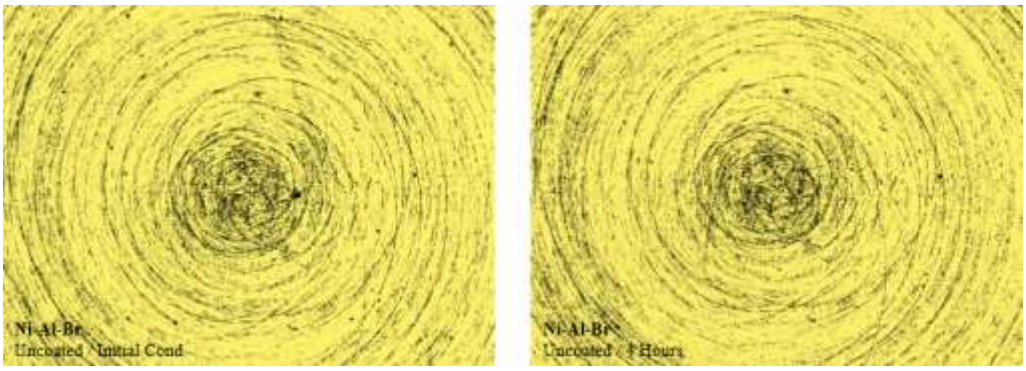

Fig. 30 – Uncoated results of Nickel-Aluminium-Bronze alloy sample

If the first and second test cases are compared, the samples in the second case have more erosion on their surface. This means that if the airflow rate is increased, this generates more bubbles and it causes more complexities in the flow. So if airflow rate is increased, this causes more erosive parts on the surface of the samples for both CU1 and CU3 alloy surfaces.

5. Conclusions

In order to investigate cavitation erosion using a cavitating air jet, an experimental study was carried out under specified conditions in bubbly flow to the sample surfaces of Manganese-Bronze (CU1) and Nickel-Aluminium-Bronze (CU3) alloy in the cavitation test rig, which is set-up for this study at ITU. Cavitation erosion on the surface of the samples was examined using a Reflective Light Microscope (RLM). Complementary experimental investigations considering different test durations and coating techniques were conducted in the cavitation test rig.

Comparisons between erosion on the surfaces of CU1 and CU3 samples for 12 hours tests have produced the following preliminary conclusions. Some of these conclusions corroborate earlier results, but most of them need confirmation through additional testing and variation of the experimental configurations.

- Performing cavitation air jet test is a simple and cheap way to investigate the resistance of different coated surfaces to cavitation erosion.
- Only larger than a certain airflow rate level generates cavitation that causes the cavitation erosion for materials.
- As the erosion test time increases, erosion on the surfaces also increases. However a quantified correlation between test time and erosion on the surface have not been obtained.
- The stand-off distance is a crucial parameter for bubble collapse effect on the sample surfaces. As the stand-off distance decreases, cavitation erosion on the sample surface increases.
- Air flow rate is an important parameter for bubble formation and as the flow rate increases, cavity (air) bubbles in the water increases nonlinearly and these bubbles increases.
- As flow rate of the air increases, erosion damage on the sample surface also increases.

Furthermore, this study is an ongoing research and highlights the need for further work in the area of generating cavitation erosion rig using ASTM standards.

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